STUDY OF RADIATION SHIELDING CHARACTERISTICS AND STRENGTH CHARACTERISTICS OF POLYSTYRENE STEEL COMPOSITE MATERIALS WITH HIGH CONTENT OF METAL COMPONENT

E.M. Prokhorenko[1], A.A. Zakharchenko[2], M.A. Khazhmuradov[2], S.A. Sokolov[2], T.G. Prokhorenko[3]

[1]Institute of Electrophysics and Radiation Technologies NAS of Ukraine, Kharkiv, Ukraine;
[2]NSC "Kharkiv Institute of Physics and Technology", Kharkiv, Ukraine;
[3]Kharkiv National Automobile and Highway University, Kharkiv, Ukraine

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INTRODUCTION

Currently, in energy, industry, medicine, and science widely use devices and equipment that are sources of ionizing radiation. In addition, high-risk areas include enterprises manufacturing various sources of ionizing radiation, deposits of radioactive elements, quarries for storing waste rock, storage and disposal sites for spent nuclear fuel (SNF) or radioactive waste (RAW), and spent equipment.

Thus, more and more people are exposed to ionizing radiation. Also, the probability of occurrence of emergency and accident situations increases. In this case, the release of radioactive elements into the environment is possible.

All these factors require the use of shielding equipment against ionizing radiation. The shielding must reduce the radiation to a safe level.

Currently, various radiation shielding materials are used. Among them, both materials with a large atomic mass (Pb, W) and materials with a low atomic mass (B, Br). Materials with a large atomic mass absorb X-rays, gamma radiation, accelerated beams of high-energy protons, ions, electrons well. Materials with a low atomic mass have a wide scattering cross-section and are effective shielding against streams of neutron.

For maximum efficiency of shielding against ionizing radiation, materials are used that use several different shielding components. These composite materials allow for maximum weakening of ionizing radiation and can also have additional properties. We can obtain materials with increased mechanical strength, elasticity, etc. Also, the use of composites allows solving the problems of reducing the weight of products. It is possible to select materials that reduce the impact of aggressive environments and high temperatures. Selection of certain components allows increasing the corrosion resistance of the material. Composite materials can increase operational characteristics.

At present, much attention is paid to the study of radiation shielding materials based on polymers with added fillers [1, 2]. Various radiation shielding additives were used as fillers. The choice of a radiation shielding component depends on the intensity of radiation and its type. Thus, effective shielding from neutrons is provided by Bi additives. The results are interesting when CdTe is used.

Previously, we studied composites with a radiation shielding component made of tungsten [3-7]. These composite materials have a wide range of applications

Composites with a steel component are of great interest [4-7]. Powder of steel is obtained from waste during the production process [8, 9]. Therefore, the cost of composites is low. The shielding properties of steel powder are low, so the thickness of the shielding layer must be large. That is, the use of polystyrene steel composite is advisable in cases where the thickness of the shielding layer is not limited. These composite materials will also be effective for radiation shielding of radioactive waste (RAW) and spent nuclear fuel (SNF) storage facilities [10].

Composite materials are characterized by several parameters. For our purposes, the most important parameters are: radiation shielding characteristics; strength and hardness characteristics. These characteristics were studied in this paper. The characteristics of composite materials based on polystyrene and steel, with a high content of steel components, were considered.

PURPOSE OF WORK

The purpose of this work is:

1. Measurement and numerical calculation of radiation shielding characteristics of materials with increased content of steel components.
2. Obtaining tensile strength on a break, characteristics for composites with steel additives.
3. Improving the technology for manufacturing composite materials based on polystyrene with a steel component.

CONDUCTING EXPERIMENTS AND DISCUSSION OF RESULTS

Experimental samples of polystyrene steel composite materials have been manufactured, which are intended to shielding against ionizing radiation [4-7]. Some of these composites have already undergone laboratory tests and have been used in production. It has been found that these composites have high characteristics.

The creation of composite materials requires solving a number of problems. It is necessary to select the base material. Depending on the type of radiation, it is necessary to determine the radiation shielding additive. It is also necessary to select a material for reinforcing the composite and creating its matrix. An important part of the work in the creation of composite materials is the development of technological processes for the production of composites.

Polystyrene PSM-115 (GOST 20282-86) was used as a base. Polystyrene is suitable for work in a wide range of temperatures. Its temperature of softening influence is 86…92 °C, temperature of melting is 196…200 °C. Polystyrene has low hygroscopicity, high water resistance, and is resistant to acids and alkalis.

It should be noted that polystyrene is resistant to ionizing radiation (electrons, ions, X-rays, gamma rays, neutrons). This is due to the fact that as a result of irradiation, two opposite processes occur in polystyrene: the process of destruction of polystyrene molecules and the process of connections of sewing together of polystyrene molecules. The rate of connections processes of polystyrene molecules is slower than the processes of destruction. However, of sewing together processes have a significant effect on the restoration of polystyrene. Strengthening of composites also occurs due to the stretching and reorientation of polystyrene chains.

To create a radiation shielding composite, it is necessary to add a radiation shielding additive to polystyrene. Steel powders (a PS-Fe-Al type composite) were used as a radiation shielding component [5-7]. However connection of separate particles of steel with polystyrene insufficient, because steel little moistens polystyrene. Therefore, another additive was used to reinforce the composite.

To create the composite matrix, highly dispersed aluminum powder was used. In the production of composite materials, aluminum powders obtained from aluminum ASD-6, 2014, 6111 were used. Aluminum powders comply with the standards specified in the documents: ISO 209-1, TU 1791-007-49421776-2011. Aluminum particles can have the following sizes: 10…20, 30…40, 60…90 μm.

For highly dispersed aluminum powder we have high mechanical interaction with polystyrene. Also, the presence of aluminum in the composite improves the volume distribution of heavy metal powders.

Improvement of equipment. The following units were used in the production of composite materials: Kuasy 100/25, Windsor SP 80. The Kuasy 100/25-1 and Windsor SP 80 units are horizontal injection molding machines. Composite materials are produced on them using the extrusion method. This equipment was used not only to produce reinforced polystyrene products, but also to refine the technology for producing composite materials.

There are certified technological processes for the production of reinforced polystyrene products for these units. The technology for producing radiation-protective composite was improved using the Kuasy 100/25-1 unit, as it has lower characteristics (injection pressure – 180 MPa, injection volume – 50 cm^3). The production of composite material, taking into account modifications and improvements, was carried out using the Windsor SP 80 unit. Its productivity is higher (injection pressure – 300 MPa, injection volume – 187 cm^3).

The production of radiation shielding protective composites is a complex process. Therefore, the equipment was improved and refined. The raw material supply system was refined and an additional device for mixing the components was added. Additional heaters are installed [5-7]. The temperature control system was also improved. Optical methods and IR radiometry methods were used to control the uniformity of mixing. For this purpose, thermal imaging devices Lend Ti-814, Fluke-10, Fluke-25 were used [11].

Some of the parts that were modified are shown in the photograph (Fig. 1).

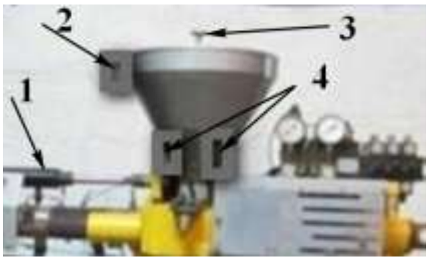

Fig. 1. Photograph of the feed system and bunker with improvements: 1 – feed motor and rotation system; 2 – motor for the blades of the raw material mixing system; 3 – IR camera for heating control; 4 – heaters

Calculation of radiation shielding characteristics. The main characteristic of composites is their radiation shielding properties. In case of real use of composites, it is necessary to know their radiation shielding characteristics.

Previously, theoretical calculations of radiation shielding properties [3-7] were performed and experimental measurements [5] were carried out for composite materials with a low content of metallic components. Good agreement between theoretical and experimental results was found.

This paper presents the results of calculations and measurements for composite materials with a high content of metallic components. They are designated as CFe05YYZZ. These composites contain five volume parts of polystyrene and ten volume parts of metallic components. The appearance of the CFe050109 sample is shown in Fig. 2.

Fig. 2. Appearance of sample CFe050901. Size of component grains: Al – 10…20 μm, Fe – 230…280 μm

Composites of the CFe05YYZZ type have an external appearance close to that of the CFe050901 sample (see Fig. 1).

The mass values and density of the composite materials are given in Table 1.

Table 1

Mass quantity of components in composite materials of the CFe05YYZZ type

Material/ density (g/cm^3)	Polystyrene (PS) mass (%)/ amount (g in 15 cm^3)	Steel (Fe). mass (%)/ amount (g in 15 cm^3)	Aluminum (Al) mass (%)/ amount (g in 15 cm^3)
CFe050109/ 2.51	14.6/ 5.5	7.86/ 20.87	24.3/ 64.52
CFe050505/ 3.89	9.43/ 5.5	39.3/ 67.41	13.5/ 23.16
CFe050901/ 5.26	6.97/ 5.5	70.74/ 89.61	2.7/ 3.42

Practical measurement of shielding characteristics is a long and labor-intensive process. Therefore, software packages were developed to calculate the attenuation of ionizing radiation. The Geant4 v 4.9.6p03 software package [12] was used for the calculation. For our purposes, the package was modified [13].

The basic parameter of efficiency of shielding protection is the relative attenuation of dose of ionizing radiation. This parameter is calculated on a mathematical formula:

$$\eta = 1 - \frac{D}{D_{air}}, \qquad (1)$$

D_{air} – is the calculated dose, in the absence of protection; D – is the calculated dose when shielding protected; η – is the degree of relative attenuation of the absorbed dose of gamma radiation by a layer of shielding protection made of a composite material. In these calculations, the effect of ionizing radiation on a biological phantom was considered.

The program code was used to obtain curves of changes in protective characteristics. Calculations were performed for samples with a thickness of 1 cm. The samples were solid. The results of the numerical calculation are shown in Fig. 3.

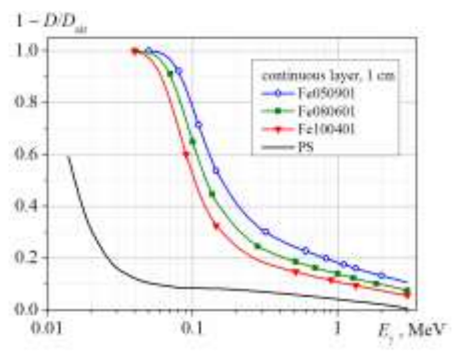

Fig. 3. Graphs of attenuation, absorbed dose of ionizing radiation for CFeXXYYZZ composites

As follows from the graphs (see Fig. 3), composite materials have fairly high radiation shielding characteristics. The best shielding indicators are demonstrated by the CFe050901 composite. It contains the maximum amount of steel powder. Half-attenuation occurs at gamma quantum energies of no more than 150 keV. At gamma quantum energies of 300 keV, no more than 30% of the gamma radiation flux is absorbed. For comparison, Fig. 3 shows graphs of composites with a lower content of steel powder. Accordingly, the radiation shielding properties of these composites are lower

Also, the absorbed dose measurements were performed experimentally. These measurements were carried out using ionizing radiation sources ^{241}Am (gamma-quanta with an energy of 60 keV) and ^{90}Sr [5, 6]. For the measurements, composite samples with dimensions of 7 × 4 × 1 cm were made.

When using the ^{241}Am source, it is necessary to study the change in the 59.54 keV photopeak. The results of the experimental measurements are shown in Fig. 4

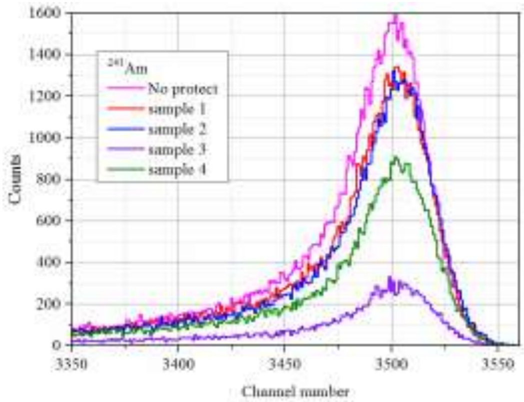

Fig. 4. Graphs of change of photopeak from the source of ^{241}Am

The change in the graphs depended on the type of composite material. For control, the protective properties of pure polystyrene were measured (light pink curve). With an increase in the amount of steel components, the protective properties of the composites also increase. The maximum absorption was obtained for the composite material CFe050901 (purple curve). The results of experimental measurements have a high coincidence with the results of numerical calculations.

An important characteristic of composite materials is strength. The strength of composites was tested on a tensile testing machine. Composite tensile testing was carried out in accordance with the requirements of GOST 11262-80 "Plastics. Tensile testing method" and ASD-3039/D3039M.

For testing on the tensile testing machine, samples of composite materials in the form of rods 12 cm long and 1 cm in diameter were used. From the experiment, one can find the tensile strength on a break, the value of relative elongation, and the yield strength.

There are known results in which composites are studied under compression [14]. Comparison of the results obtained in our works [5-7] with the results obtained in work [14] allows us to identify general patterns of change in strength characteristics.

The main parameter that is studied during the experiments on tensile testing machines is the tensile strength on a break. It was found that the tensile strength on a break of composites is higher, the higher the dispersion of steel and aluminum powders. Also, the tensile strength on a break strongly depends on the ratio of the volumes of the steel and aluminum components. The higher the volume content of aluminum, the higher the tensile strength on a breakt.

The accuracy control of the tensile testing machine was checked during tensile testing of pure polystyrene samples. The tests were carried out at a temperature of 290 K. The rupture occurred with stretching. In this case, a neck was formed. The elastic modulus was 2.1 GPa. The relative elongation was equal to 95…96%. Pure polystyrene had a high yield point, which was equal to 24…25 MPa. The value of tensile strength on a break was equal to 22 MPa

At the next stages of the research, the tensiles of strength of composite materials of class CFe05YYZZ were measured.

Since composites are used in various weather conditions, the tensile testing was carried out at three fixed temperatures (250, 290, 320 K). The size of grains of aluminum was 10…20 μm. The size of steel grains was 230…280 μm.

The numerical results of the measurements are given in Table 2.

Table 2

Tensile strength on a break for composite materials of type CFe05YYZZ

Tape \T(K)	250 K (MPa)	290 K (MPa)	320 K (MPa)
PS	37.0	23.0	22.0
CFe050901	22.2	22.4	22.3
CFe050505	22.6	22.8	22.7
CFe050109	23.1	23.4	23.3

It was found that the maximum tensile strength is achieved at a temperature of 290 K. At temperatures of 250 K, embrittlement of polystyrene is possible. At temperatures of 320 °K, softening of polystyrene occurs and the composite material "stretches".

Thus, on the basis of the got results, we can select the necessary composite material. In this case, the composite has certain, predetermined parameters: radiation shielding characteristics and strength characteristics. That is, for each specific case, we can select a composite material with the required properties.

CONCLUSIONS

1. Experimental samples of composite materials of the CFe05YYZZ series were manufactured. The modes of operations of the equipment and the sizes of the component grains were selected experimentally.

2. Numerical calculations of the attenuation coefficients of ionizing radiation for composites with a radiation shielding component in the form of steel powder were performed. Cases were considered when the amount of the metal component was greater than the amount of polystyrene. It was found that the composite material CFe050901 had the maximum radiation shielding characteristics.

3. Mechanical tests of tensile strength on a break were carried out for composites CFe050109, CFe050505, CFe050901. The tests were carried out at temperatures of 250, 290, 320 K. It was found that the maximum tensile strength on a break occurs at a temperature of 290 K.

4. It was found that the tensile strength was mainly increased by the aluminum component. It was determined that composites with the smallest particle sizes of the components had the highest tensile strength on a break.

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